Advances in Concrete Construction, *Vol. 17, No. 3 (2024) 127-133*
https://doi.org/10.12989/acc.2024.17.3.127

Flexural evaluation of Textile Reinforced Concrete Panel (TRC) with mesh pre-stretching effect

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(*Received August 18, 2023, Revised July 11, 2024, Accepted July 16, 2024*)

Abstract. Textile reinforced concrete (TRC) has gained attention as a viable alternative to conventional reinforced concrete due to its improved mechanical properties and design adaptability. Despite significant research into the mechanical properties of TRC, studies regarding the flexural effect of pre-stretching with different numbers of textile reinforcements are currently limited. Therefore, this research focuses on assessing the flexural characteristics of TRC panels with the incorporation of mesh pre-stretching. Additionally, the study compares the flexural behaviour between alkali-resistant (AR) glass fibre TRC and carbon fibre TRC. A three-point bending test was conducted to assess the flexural behaviour of TRC, investigating the impact of the number of textile layers and the application of pre-stretching on flexural strength and post-cracking stiffness. The findings, exhibited by the flexural stress vs. displacement curve, indicate that applying pre-stretching to carbon fibre TRC effectively increases the flexural strength of carbon textiles and enhances post-cracking stiffness. Moreover, the greater the number of carbon textiles, the higher the flexural stress of the specimens, provided the textiles are placed in the tensile zone. Nevertheless, when comparing carbon fibre TRC with AR glass fibre TRC, it is found that the increase in flexural strength is more significant for carbon fibre TRC. Overall, applying pre-stretching to carbon fibre significantly improves the TRC's flexural performance, specifically during the post-cracking stage and in crack distribution. Furthermore, due to the higher elastic modulus and tensile strength of carbon fibre, TRC reinforced with carbon textiles shows greater flexural strength and ductility compared to AR glass fibre TRC.

Keywords: AR-glass textile; carbon textile; flexural behaviour; textile reinforced concrete; TRC

1. Introduction

Steel rebar has been widely used as tensile reinforcement in reinforced concrete due to its high ductility, modulus of elasticity, and thermal expansion compatibility, reducing the risk of concrete-reinforcement debonding. However, steel reinforcement in reinforced concrete is susceptible to corrosion attack (Attia *et al*. 2022, Hosseini 2022), and the limitation in shape and size of steel-reinforced concrete structures has led the construction industry to seek conceivable alternative reinforcement in reinforced concrete structures (Gries *et al*. 2016). Several alternative reinforcements, such as fibre reinforcement (Attia *et al*. 2022, Khan *et al*. 2023, Panzera *et al*. 2013), coated reinforcement (Cheng *et al*. 2005, Venkatesan *et al*. 2006), fibre-polymer composites reinforcement (Meskhi *et al*. 2022), and bamboo (Archila *et al*. 2018, Rahim *et al*. 2020), have been widely studied as replacement steel reinforcements in reinforced concrete structures.

Textile-reinforced concrete (TRC) is one of the alternative advanced composite materials developed in the 1980s that utilize textile reinforcements like alkali-resistant (AR) glass, carbon, polymer, or aramid textiles in the fine-grained cement-based matrix. It has gained popularity in the last two decades due to its non-corrosive nature, high fire resistance, and shape flexibility of structure (Colombo *et al*. 2013, Gries *et al*. 2016, Koutas *et al*. 2019). TRC is commonly used in facade construction and load-bearing structures such as lightweight, thin-walled, ventilated façade elements due to its lower costs in material, anchorage, and transportation (Hegger *et al*. 2008, Hegger and Voss 2008). Past studies have been done to study the effect of incorporating carbon (Halvaei *et al*. 2020a, b, Ramesh *et al*. 2024, Rebecca and Flávio 2020), AR glass (Butler *et al*. 2010, Mohan and Madhavi 2024, Park *et al*. 2017), and basalt textile (Du *et al*. 2018b, Gopinath *et al*. 2015), as reinforcement. To investigate the effect of mesh size and volume fraction on the flexural properties, Halvaei *et al*. (2020b) concluded that reducing the textile mesh sizes from 20 to 2 mm significantly boosted the flexural load and toughness of the TRC. On the other hand, Barhum and Mechtcherine (2012) found that the incorporation of 1.0% short, dispersed AR glass fibers in the material led to a 1.5-fold increase in first-crack stress, while the incorporation of 1.0% of short, dispersed carbon fibers resulted in a 2-fold increase in first-crack stress. Despite the presence of more

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http://www.techno-press.org/?journal=acc&subpage=7
ISSN: 2287-5301 (Print), 2287-531X (Online)

and finer cracks in the specimens with embedded short fibers, there was only a slight improvement in tensile strength (Barhum and Mechtcherine 2012). As mentioned earlier, the cover thickness can be drastically reduced in TRC compared to conventional reinforced concrete structures due to the non-corrosive nature of fibre textiles. However, it noted that the thin concrete covers have a higher tendency to spall off due to the curvature effect of the textile materials when subjected to loadings. Such curvature effects can be reduced to a negligible degree if the materials are pre-tensioned. Furthermore, pre-tension on the textile reinforcement significantly improved structural members' mechanical properties and lifespan (Du *et al.* 2018a). Meyer and Vilkner (2003) studied the flexural behaviour of pre-tensioned aramid TRC by conducting a 3-point bending test. The results showed that applying textile mesh pre-tension has improved the post-cracking flexural stiffness and bearing capacity; however, it decreases the ductility of the specimens (Meyer and Vilkner 2003).

The present work investigates the effects of carbon and AR glass textile layers and textiles' pre-stretching effects on the panels' flexural strength. The comparison of flexural strength between carbon and AR glass fibre TRC is also presented.

2. Materials and method

2.1 Cementitious matrix

Engineered cementitious composite (ECC) with the self-consolidating property was used as the matrix of TRC in this study. The mix proportion of ECC adopted was referred from the research conducted by Li (2008). The quantity of each material was calculated based on the ratios against OPC, as shown in Table 1. Furthermore, a compressive strength test was carried out following ASTM C109 to determine the compressive strength of the ECC matrix. The average compressive strength of the 50 mm ECC cube at 7 and 28 days was 42.4 MPa and 57.4 MPa, respectively.

2.2 Carbon textile

Fig. 1(a) shows the textile reinforcements used in this research. Horse Construction Co., Ltd manufactured the carbon textile used in this study. The tensile strength of the warp and weft per unit width of the carbon textile is 31 kN/m, having a density of 1820 kg/m^3, while the fibre thickness is 0.047 mm. The carbon textile has an average tensile strength of 4900 MPa, a tensile elastic modulus of 234 GPa, and an elongation of 1.70 % while impregnating with epoxy resin. The opening of the carbon textile used is 20 × 20 mm.

Table 1 Mix proportion of ECC

Material	Ratio	Quantity (kg/m^3)
OPC	1	583
Fly ash	1.20	700
Water	0.56	327
Sand	0.80	466
Superplasticizer	0.01	6
PVA fibre (Volume %)	0.02	26

2.3 AR glass textile

Fig. 1(b) shows The AR glass textile used was supplied by Nippon Electric Glass Co., Ltd. The density of the AR glass textile is 2800 kg/m^3, with Young's modulus of 74 GPa and tensile strength of 1500 MPa. The percentage of the opening area of the AR glass textile is about 62.4 % and, the aperture size of the mesh was 2.2 × 2.5 mm.

2.4 Specimen preparation

In this study, all the TRC specimens had the exact dimensions of 500 mm (length) × 75 mm (width) × 16 mm (depth). The specimens were prepared using the laminating method, and the specifications of the TRC specimens are shown in Table 2. Three nominally identical specimens were tested for each experimental case, and the average results were calculated. The steel moulds used in this study are shown in Fig. 2. The positioning of each textile layer is controlled by placing the ends of the textile meshes between end plates. The end plates consist of two different thicknesses: 1.5 mm and 2 mm. For instance, to achieve 3 mm thickness, as shown in Fig. 3, two end plates with 1.5 mm were inserted into the screw located at the end of the mould, hence maintaining the distance of the textile layer-to-layer during the casting. The carbon textiles were placed in the specimen's tensile zone. Additionally, the carbon was pre-stretched by tightening the screw at the end of the mould as shown in Fig. 3.

2.5 Tests

A 3-point bending test was conducted to study the flexural strength of the TRC specimens with a loading rate of 1.00 mm/min with the span length set at 380 mm, as shown in Fig. 4. The flexural strength of the specimens is then calculated using the Eq. (1) below

$$\sigma = \frac{1.5PL}{bd^2} \tag{1}$$

Table 2 Designation of samples

Material	Type of textile	Number of textile layers	Reinforcement ratio	Pre-stretch
CS	-	0	0	-
CT1	Carbon	1	0.36	No
CT2	Carbon	2	0.72	No
CT3	Carbon	3	1.08	No
ART1	AR Glass	1	0.38	No
ART2	AR Glass	2	0.76	No
CT1PS	Carbon	1	0.36	Yes
CT2PS	Carbon	2	0.72	Yes
CT3PS	Carbon	3	1.08	Yes

(a) (b)

Fig. 1 Physical properties of (a) Carbon fibre textile; (b) AR glass fibre textile

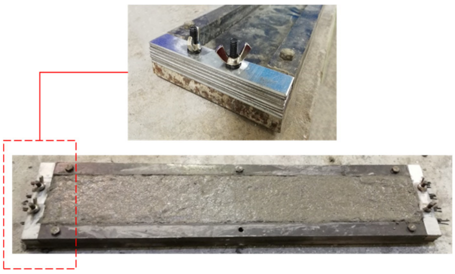


Fig. 2 Designed end of steel mold

Where σ = flexural strength, P = flexural load, L = span length, b = width of specimen, d = thickness

3. Experimental results and discussion

3.1 Effect of the number of textile layers

Fig. 5 shows the flexural stress-displacement curve of TRC specimens with a different number of textile layers. Meanwhile the ultimate flexural stress was depicted in Fig. 6. Generally, all specimens show linear-elastic behaviour under flexural loading at the pre-cracking stage. However, it was interesting to note that the flexural stress of the TRC specimens was within a similar range, 5.9 MPa - 10.2 MPa, when the first crack occurred. This result shows that the first crack stress mainly depends on the matrix strength. At the post-cracking stage, multiple drops were observed from CS, ART1, and ART2 curves. This strain hardening property is due to the bridging process of short dispersed PVA fibre and textile fibre, which transfers the loads from the crack plane back to the matrix of ECC, causing another crack to form. The process continues, resulting in the formation of numerous cracks. When the ultimate tensile strain of the textile fibre is reached, the curve experiences a rapid drop, and the specimens fail. The average maximum flexural stress of CS, ART1, and ART2 are recorded as 7.5 MPa, 8.83 MPa, and 11.07 MPa, respectively. The effect of incorporating 1 layer and 2 layers of AR glass textile showed 17.73% and 47.60% improvement in the average maximum flexural stress compared to CS.

On the other hand, the average maximum displacement of all TRC specimens is higher than the control specimen due to the incorporation of carbon fibre textiles. Therefore, adding carbon fibre enhances the flexural behaviour thus, increasing the ductility during the flexural load applied to the specimens. Nevertheless, it is observed that the embedment of AR glass fibre textiles increases the ductility of the specimens. As a result, an increase of 11.68% in average maximum displacement has been recorded for ART1, while a further increase of 11.93% for ART2 compared to ART1.

The specimens from CT1, CT2, and CT3 show an apparent increase in the load-bearing capacity, as shown in Fig. 5 and Table 3. Compared with CS, the effect of embedding one layer of carbon textile into the ECC matrix as the primary reinforcement is proven by a significant increase of 256.93% based on average ultimate flexural stress. In contrast, the average ultimate flexural stress after incorporating 2 and 3 layers of carbon textile has increased by 316.40% and 290.67%, respectively, compared to CS.

Furthermore, the increment of average flexural stress is recorded at 16.42% after increasing the number of carbon textiles from 1 to 2 layers. An insignificant reduction of

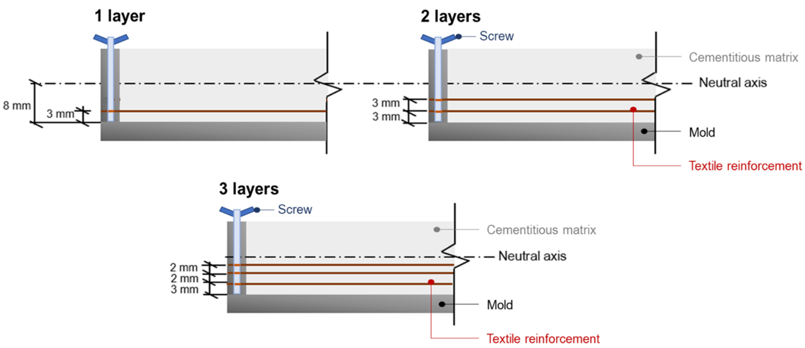
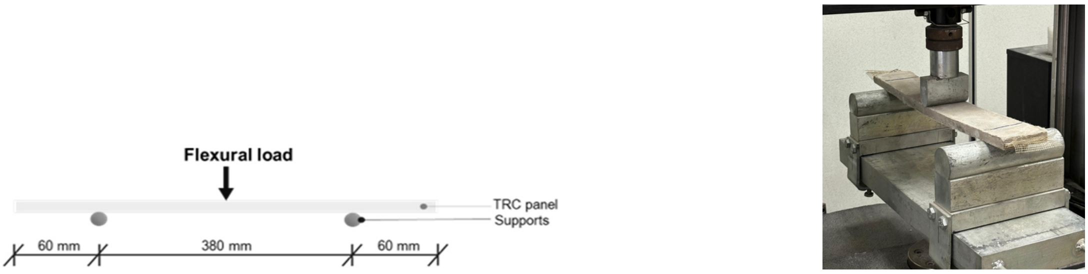


Fig. 3 Position of textile reinforcement



(a) (b)

Fig. 4 Three-point bending test (a) schematic diagram; (b) experimental setup

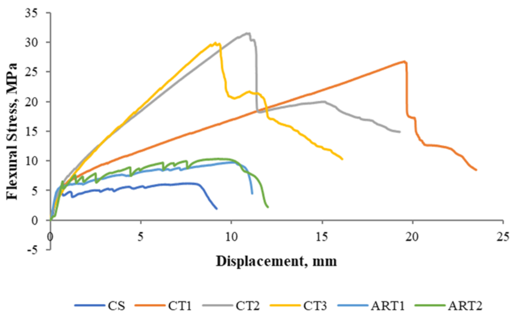


Fig. 5 Flexural stress vs. displacement

Table 3 Experimental results

Specimen	Average first crack flexural stress (MPa)	Average ultimate flexural stress (MPa)	Average maximum displacement (mm)
CS	5.9	7.5	9.2
CT1	6.9	26.8	23.1
CT2	6.9	31.2	19.4
CT3	5.8	29.3	15.7
ART1	5.0	8.8	10.2
ART2	6.3	12.9	11.5
CT1PS	6.3	31.3	16.2
CT2PS	10.1	40.6	18.8
CT3PS	10.2	37.4	19.2

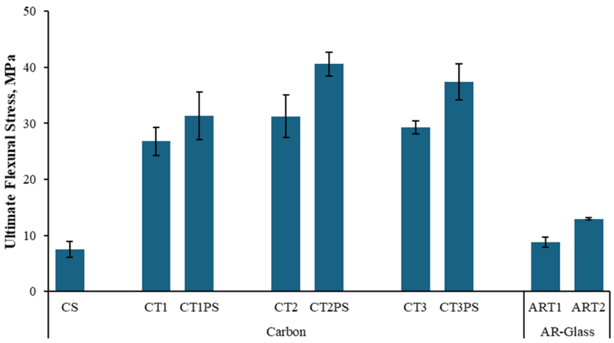
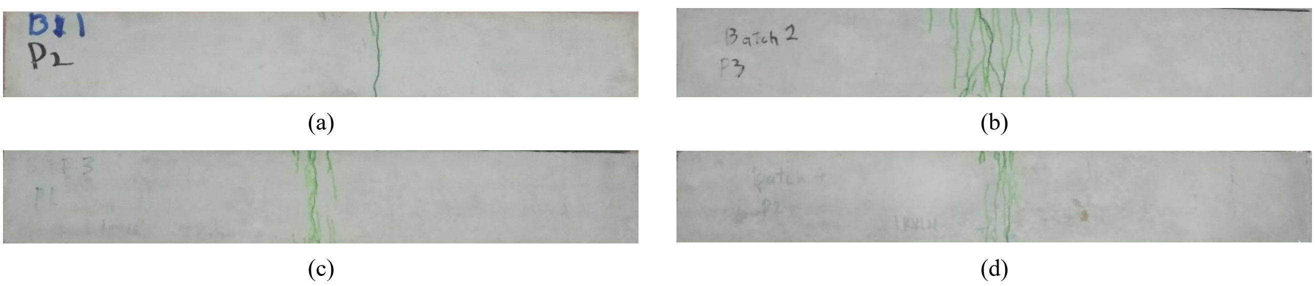


Fig. 6 Ultimate flexural stress results

6.30% is noted as the number of carbon textiles increases to 3 layers. A similar observation was also reported by Du *et al*. (2018a), where the ultimate flexural stress of TRC with two layers of carbon textile increased by 279.03% compared to the control specimen. The possible reason causing an insignificant difference between CT2 and CT3 in average ultimate flexural stress is that the position of the third layer was close to the neutral axis, which was about 1 mm, causing it to be a non-contributing layer in resisting the flexural loading. Another possible reason is that the ECC matrix layer of CT3, 2 mm, was thinner than CT2, 3 mm, causing the tensile strength of the matrix to be slightly weaker. The higher the number of carbon textiles, the greater the flexural stress of the specimens, provided the textiles are placed in the tensile zone.

On the other hand, the maximum displacement of carbon fibre TRC without pre-stretch force decreases as the number of textiles embedded increases. The average maximum displacement reduces by 15.97% as the number of carbon textiles increases from 1 to 2 layers. Further, it reduces by 19.05% as three carbon textiles are incorporated despite insignificant changes in average ultimate flexural stress. Du *et al*. (2018a) showed similar behaviour where the ultimate deflection of carbon fibre TRC decreases as the number of textiles embedded increases. The crack



(a) (b) (c) (d)

Fig. 7 Crack patterns of TRC specimens; (a) CS; (b) CT1; (c) CT2; (d) CT3 pattern can further support this, as shown in Fig. 7(a). The crack pattern of the control specimen is observed where there is a single crack in the middle of the span. From Figs. 7(b)-(d), incorporating carbon textiles is noticed as the number of cracks increases, and the cracks spread wider instead of a single major crack. This is due to increased flexural strength after adding carbon textile, allowing more cracks to form before it fails. The decreasing trend of average maximum displacement observed in CT1, CT2, and CT3 can be supported by the reducing area of the crack spreads.

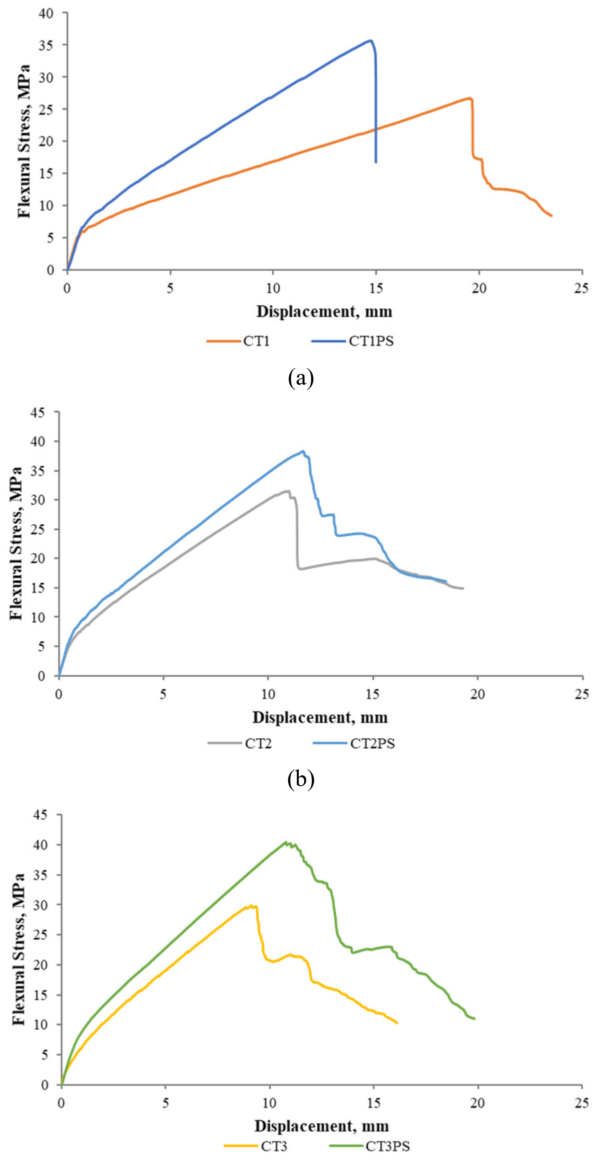
The slope of the graphs for CT1, CT2, and CT3 was less steep in the post-cracking stage compared to the pre-cracking stage, indicating a reduction in the specimen's stiffness. However, a trend can be observed: the number of carbon textiles increases, and the extent of stiffness reduction decreases. According to Du *et al.* (2018a), as the load rose, the crack width widened, and cracks migrated upwards in the post-cracking stage. As a result, the TRC specimen's neutral axis shifted upward, indicating the carbon textiles' contribution to section stiffness, as the textiles sustained the tensile stress at the fractures. As a result, the TRC specimens' post-cracking flexural stiffness could be reduced less as the number of textile layers increases.

3.2 Effect of pre-stretching on carbon fibre TRC

The effect of pre-stretching the textiles can be observed in Fig. 8. A noticeable trend can be noticed in the figures where the ultimate flexural load is higher for specimens with pre-stretching than those without pre-stretching. Based on Table 3, the average ultimate flexural stress for one layer of carbon textile increased by 16.92%. In contrast, the average ultimate flexural stress increased by 29.91% for specimens with two layers of carbon textile. The average ultimate flexural stress for three layers of carbon textile also shows the same trend, increasing by 27.54%. Du *et al.* (2018a) explained the increment after stretching, where the textile retracted after the applied stretching force was released. As a result, the cross-section of the textile rises because of Poisson's ratio, causing the textile to compress against the matrix. Hence, the bonding between the textile and matrix improves, leading to stronger flexural strength. Additionally, the textile layer in the tension region provides pre-compressive stress that contributes to the resistance in tensile loading when applied to bending force.

Besides, the slope in the post-cracking stage for all graphs shows a similar trend in which the batches with pre-stretching have a steeper slope than those without pre-stretching, indicating that the stiffness reduction is lesser. Pre-stretching the textiles decreases the reduction of stiffness in the post-cracking stage. This observation was similar to the finding reported by Vilkner (2004), where the application of prestressed textiles not only slowed down the development of distributed cracking but also increased the stiffness of the section in the post-cracking stage. However, it must be noted that CT3PS has a lower average ultimate flexural stress than CT2PS, which exhibited a similar trend as Section 3.1.

The crack pattern of CT1PS, CT2PS, CT3PS, CT1, CT2,



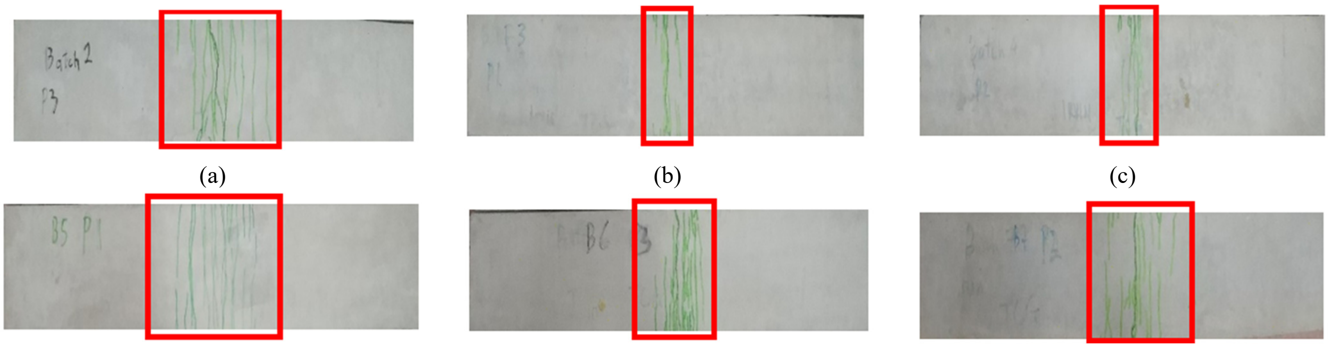
(c)

Fig. 8 Flexural stress vs displacement; (a) CT1 vs CT1PS; (b) CT2 vs CT2PS; (c) CT3 vs CT3PS

and CT3 are shown in Fig. 9. It is noticed that more cracks could be observed for pre-stretched specimens. As discussed, applying pre-stretching force leads to a higher average ultimate flexural strength of the TRC specimens. Hence, more cracks are formed before the specimens fail.

3.3 Comparison between carbon fibre TRC and AR glass fibre TRC

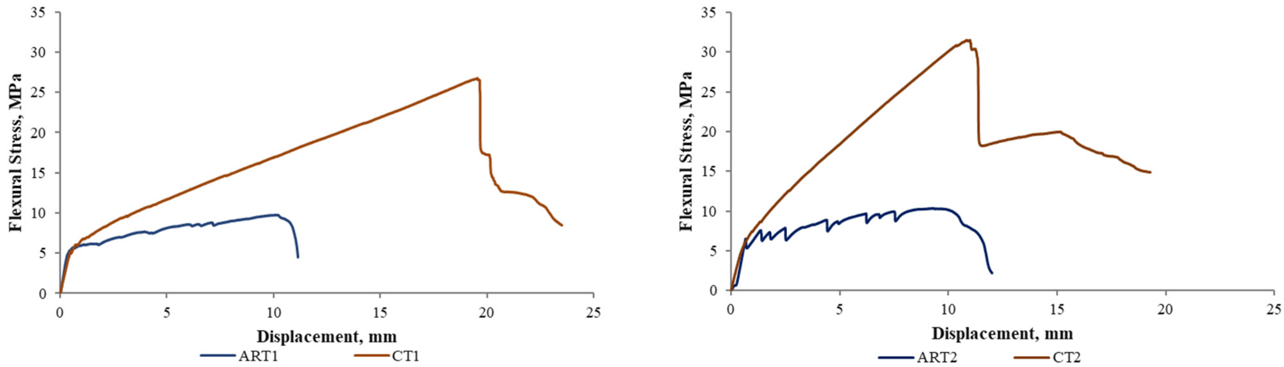
Fig. 10 shows the graphs of flexural stress against displacement for both AR glass fibre TRC and carbon fibre TRC. Again, it was found that carbon fibre TRC had a smoother and steeper slope than AR glass fibre TRC, regardless of the number of textiles. It is observed that the average maximum displacement of the specimens embedded with carbon textile is significantly higher than that of AR glass textile, indicating better flexural performance and thus contributing to the global ductility of the TRC specimen.



(a) (b) (c)

(d) (e) (f)

Fig. 9 Cracking of samples without pre-stretched: (a) CT1; (b) CT2; (c) CT3; and with pre-stretched: (d) CT1PS; (e) CT2PS; (f) CT3PS.



(a) (b)

Fig. 10 Flexural stress vs displacement; (a) 1 Layer; (b) 2 Layers

The average ultimate flexural stress of ART1 was 8.83 MPa, while the average ultimate flexural stress of CT1 was 26.77 MPa, a 203.17% difference.

For two layers of textile, the average ultimate flexural stress of AR glass fibre TRC was 11.07 MPa. In contrast, the average ultimate flexural stress of carbon fibre TRC is 31.23 MPa, an 182.11% difference. Similarly, Ramesh (2024), reported that the improved flexural stiffness of TRC was evident with carbon textile reinforcement due to their higher tensile strength and elastic modulus and resulted in improved load carrying capacity at larger deflection. The significant change in slope, better ductility, and increment of ultimate flexural stress may be explained by the more robust tensile strength and modulus of elasticity of carbon textile compared to AR glass textile, which compensates for the weak tensile strength of the matrix and helps to sustain the tensile stress from the matrix.

4. Conclusions

This paper examines the effect of the number of carbon and AR glass textiles and the application of pre-stretch on carbon textiles through a 3-point bending test. The following conclusions were drawn based on the experimental results:

- As the number of carbon or AR glass textile layers increases, the TRC specimen's flexural strength increases.
- The increment in flexural strength is more significant for carbon fibre TRC, where a 256.93% increment is observed in one layer of carbon textile, 316.40% is recorded for two layers of carbon textile, and 290.67% for three layers of carbon textile.
- Incorporating one layer of AR glass textile increased the flexural strength by 17.73%, while a 47.60% increment is observed for two layers of AR glass textiles.
- Applying pre-stretch on carbon fibre TRC effectively increases the flexural strength up to 16.92% for one layer of carbon textile and 29.91% for two layers of carbon textile, while post-cracking stiffness increases as well due to the increase in the cross-sectional area after releasing the force.
- In comparison, carbon fibre TRC shows greater flexural strength and ductility as compared to AR glass fibre TRC, with a 203.17% difference for one layer of textile and 182.11% difference for two layers of textile due to the higher elastic modulus and tensile strength of carbon textile.

Acknowledgments

The authors are gratefully acknowledged the Fundamental Research Grant Scheme (FRGS/1/2020/TK01/UM/02/2) provided by Ministry of Higher Education in supporting this works.

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